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Cylindrical Fiberoptic Light Diffuser for Medical Applications

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Background and Objective: **A cylindrical light diffuser has been developed mainly for medical applications, including photodynamic therapy (PDT), in particular interstitial PDT, PDT of the bronchi, or intravascular PDT.**
Study Design/Materials and Methods: **The diffuser is based on a polymer optical fiber. The coupling of the light out of the core is controlled by the roughness mechanically induced on the surface of the core. The light is then isotropically diffused by a thin layer of a scattering medium. The active length can be 100 mm or more, whereas the outer diameter is 1 mm or less. The diffuser is flexible and can be introduced in tissue though a hypodermic needle.**
Results: **The main property of this light diffuser is the homogeneity of the light intensity emitted along its whole active length and around its circumference (360°). Various intensity profiles can be made, including M-shape profiles for a homogeneous irradiance (±10%) at a certain depth in the tissue. Furthermore, the diffuser is essentially isotropic and its optical properties are hardly dependent on wavelength.**
Conclusions: **A diffuser for interstitial and intraluminal PDT has been developed. It is flexible, homogeneous, independent on wavelength, and can be made with a very high length-to-diameter ratio.**

Key words: **intravascular phototherapy, interstitial phototherapy, light diffuser, photodynamic therapy**

INTRODUCTION

The coupling of light between an optical fiber, which conducts the light to a diffusing segment or diffusing tip, and the actual diffusing medium can be effected using a so-called frontal geometry (Fig. 1a) or a radial geometry (Fig. 1b).

A large proportion of the light diffusers used in photodynamic therapy (PDT) in the hollow organs, as, e.g., the upper aerodigestive tract, the tracheo-bronchial tree, and the esophagus [1], are based on frontal coupling [2]. The same holds for interstitial treatments. One of the major inconveniences of this geometry is that the concentration of the particles in the scattering medium generally is not constant. It is actually made to increase with the distance traversed through the scattering medium, so as to cause a homogeneous light intensity distribution in the tissue near the surface of the light distributor. This increasing concentration of light-scattering particles compensates for the loss of intensity of nonscattered light along the main cylindrical axis due to light scattering. Of course, more complicated light intensity profiles can be attained by varying the local concentration of particles in the diffusing medium in the appropriate way. Inhomogeneous particle concentration profiles are clearly more difficult actually to produce than homogeneous ones. Hence, in general one tends to reduce the problem by having 3–5 zones, each with its appropriate scattering particle concentration.

Light-diffusing tips based on the principle of radial coupling have been developed using optical

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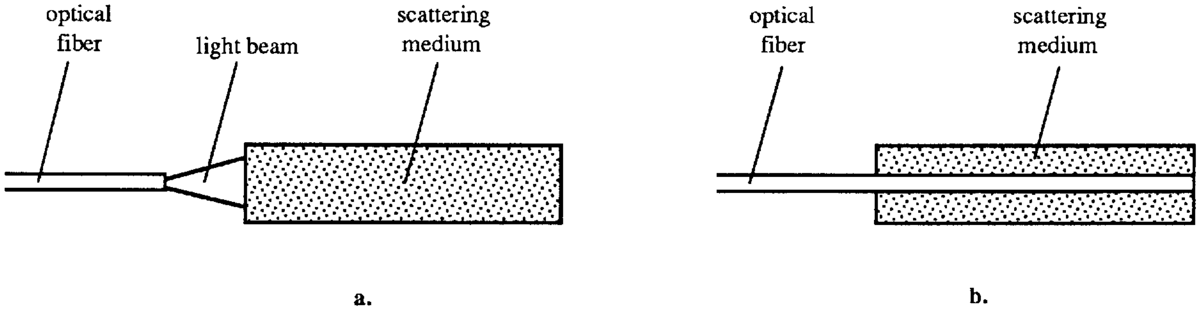

Fig. 1. Different types of coupling between optical fiber and diffusing tip: (a) frontal coupling, (b) radial coupling.

fibers with a quartz core and polymer cladding (typically hard-clad silica HCS, or plastic-clad silica PCS). The buffer and the cladding are removed to be replaced by a material that has a refractive index comparable or larger than that of quartz, e.g., acrylic copolymer [3], epoxy [4], which is generally loaded with TiO_2 particles for scattering. Such a fabrication procedure thus requires that the core is denuded for some time, which tends to render the fiber extremely fragile, possibly due to hydration of the silica surface. As the buffer, and hence its inherent mechanical support, has been removed in this process, the core of the optical fiber is supported only by contact with the scattering medium. Such diffusing tips can thus be rather rigid and break easily, rendering, e.g., an interstitial implantation dangerous. Nevertheless they have occasionally been used for subcutaneous treatments and on animals [4].

MATERIALS AND METHODS

The light diffuser proposed here is based on an optical fiber with a polymer core. In our particular case the fiber was from Toray Industries (Japan) with a core of polymethylmethacrylate with a refractive index of n = 1.492 and a cladding of fluorinated polymer with n = 1.419. The numerical aperture N.A. = 0.46 corresponds to an acceptance angle of 55°. These fibers have an attenuation of ~0.13 dB/m at 514.5 nm, 0.47 dB/m at 630 nm, and 0.15 dB/m at 650 nm.

In our fabrication procedure, the cladding is removed mechanically, which causes a roughening of the surface of the core. The core is then covered with a layer of silicone elastomer by dipping it in the nonpolymerized substance, in this case Rhône-Poulenc Rhodorsil RTV 141, which has a refractive index of n = 1.406 after polymerization and which is essentially transparent at the wavelengths of interest. On top of this layer, another is added, which consists of silicone elastomer loaded with light-scattering particles, in this case TiO_2 with a diameter of ~200 nm. The change of refractive index between the core and the surrounding layers obtained in this way is thus essentially identical to that between the core and the original cladding. The escape of the light from the core is effectively governed by the purposely introduced local roughness of the core surface. Nevertheless, as the waveguide condition of the optical fiber is still essentially conserved, a large fraction of the light continues its way in the core. This fraction can be controlled by changing the roughness of the core surface. The light escaping from the core is pitched in the forward direction, with an intensity maximum at ~45° from the main (Z) axis of the core as indicated in Figure 2.

The first layer of silicone (without particles) is interposed between the core, where the highest light intensity is, and the scattering zone. Thus interaction between the evanescent wave of the high light intensity reflected at the core surface, on the one hand, and the scattering particles, which may absorb this light, on the other hand, is negligible, and possible strong local heating due to absorption at the particle sites is avoided. After polymerization of the first silicone layer around the core, the device is inserted in the outer tube, which forms the exterior of the fiber tip and which is filled with a nonpolymerized silicone solution containing a chosen concentration of scattering TiO_2 particles. The effect of the silicone layer containing the scattering particles is to render the forward pitched light distribution leaving the core essentially isotropic. The fiber tip is advanced until it touches the end of the tube, which sometimes consists of a mirror surface that re-

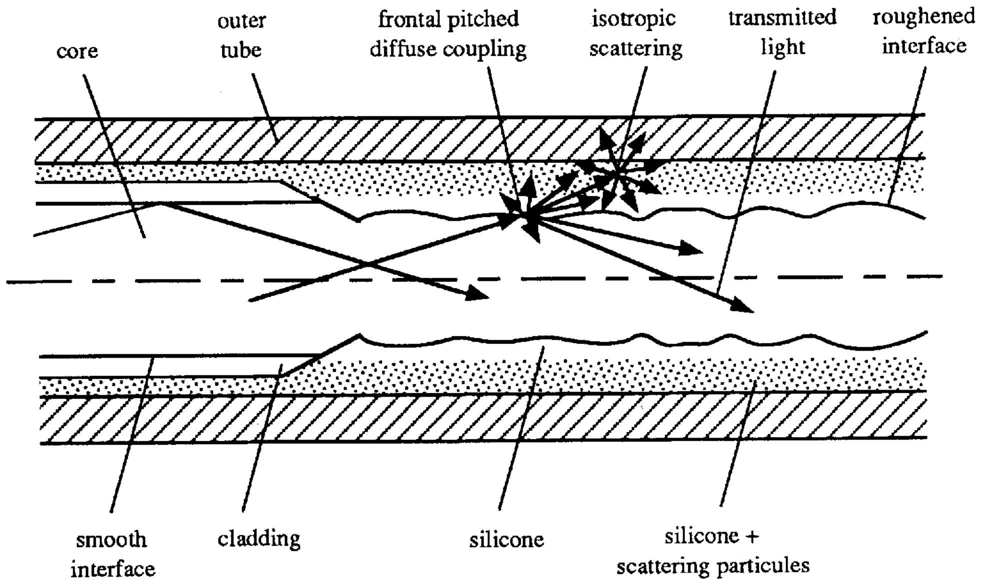

Fig. 2. Schematic diagram showing the details of the present radial coupling light-diffusing tip.

flects part of the light back down the core. Then, the solution is allowed to polymerize. The outer tube was made either of PTFE (n = 1.35) or of polyamide (n = 1.51). In the former case the difference in refractive index between silicone (n = 1.406) and tube (n = 1.35) is such that a waveguide effect is created where all light with <20° angle of incidence with the surface is internally reflected. The light with a higher angle of incidence is refracted and passes on into the tissue (n = 1.36) on the outside of the tube due to the nearly negligible change in refractive index between the PTFE and the tissue. In the latter case (polyamide outer tube with n = 1.51), it is mainly the difference between the refractive index of the silicone (n = 1.406) and the refractive index of the tissue (n = 1.36) that is responsible for the waveguide effect. This leads to essentially the same angles of incidence with the surface between 0° and 20°, which are internally reflected. However, the light distribution when entering the tissue is isotropic, due to refraction at the surface. Both tubes (PTFE and nylon) thus contribute to the further homogenization of the optical output via this supplementary waveguide effect.

A fiber with a core of 500 μm diameter enables us to produce light-diffusing tips with an outside diameter of <1 mm. Tips with a quite homogeneous light distribution have been made with "active" light-emitting length as long as 100 mm. Figure 3 schematically shows such a light diffuser with some of the typical dimensions that can be easily produced using commercially available materials.

Figure 4 shows a photograph of a 10 cm long diffusing tip based on this principle, which is emitting green light at 514.5 nm. At the end of the diffusing tip, the light can be allowed to traverse a transparent stopper or diffused in the forward direction out through the tip, or the mirror can be placed as indicated in Figure 5, where the back reflection from the mirror helps to homogenize the cylindrical radial light diffusion and decreases losses. The extremity of the light diffuser can then be cut at an angle similar to the tip of a hypodermic syringe as shown in Figure 5c, or other possible tip designs can be applied.

RESULTS AND DISCUSSION

The light intensity distributions parallel to the Z axis have been measured using a special microscopic omnidirectional fiberoptic light detector [5] in an optical tissue phantom [6]. The phantom that simulates tissue optical properties in the visible ~630 nm consists of 1.22 ml ink (rotring variograph) and 159 ml of 20% Lipovenös (clinically used emulsion, Fresenius, Germany) added to 6 l H_2O. This results in $\sigma_s' \approx 1\ mm^{-1}$ and $\sigma_a \approx 0.06\ mm^{-1}$. Figure 6 a,b shows the measurement of the light intensity (arbitrary units) as a function of the distance along the Z axis of the diffusing tip measured at different distances between the surface of the tip and the omnidirec-

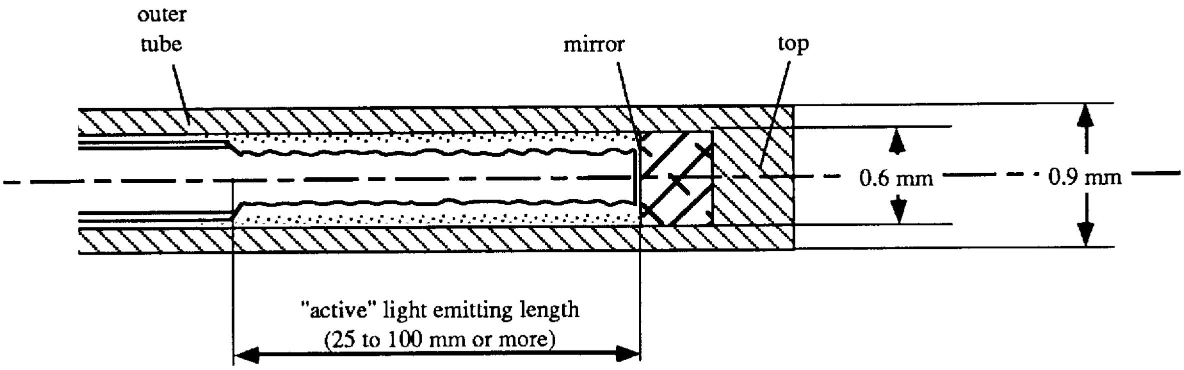

Fig. 3. Typical dimension of the present light diffusing tip.

Fig. 4. Flexible optical fiber tip (10 cm long) of 1 mm external diameter with homogeneous distribution of light intensity in the visible (green).

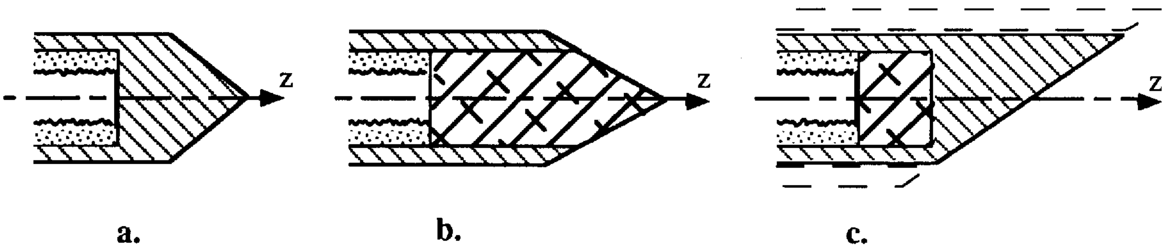

Fig. 5. Different solutions for the end of a diffusing fiber: (**a**) transparent tip with some forward illumination, (**b**) with mirror and needle, (**c**) for introduction via a hypodermic needle and possible use in interstitial therapy, also with mirror.

tional detector. Figure 6a shows such measurements in the phantom with light at 630 nm being diffused from the tip for a typical light distributor. The different curves from top to bottom represent increasing distances between the fiberoptic surface and the detector: 0 mm, 1 mm, 2.5 mm, 5 mm, 10 mm, and 15 mm. The "active" length of this diffuser was 100 mm. The optical fiber had an external diameter of 0.75 mm, whereas the internal diameter of the outside tube was 0.8 mm. The outside diameter of the exterior tube was 1.1 mm, and the tip terminated in a reflecting mirror. As can be seen, the relatively small inhomogeneities that exist at short distances from the fiber surface (±25%) are smoothed out as distance increases and light intensity decreases. Smoother intensity distributions right at the surface of the fiber can be obtained by paying more attention to the roughening procedure of the core; however, that is beyond the present scope. For comparison, the distribution of the same fiber tip is shown in air in Figure 5b for a distance between the detector and tip surface of 0 mm.

A second example of results obtained with a

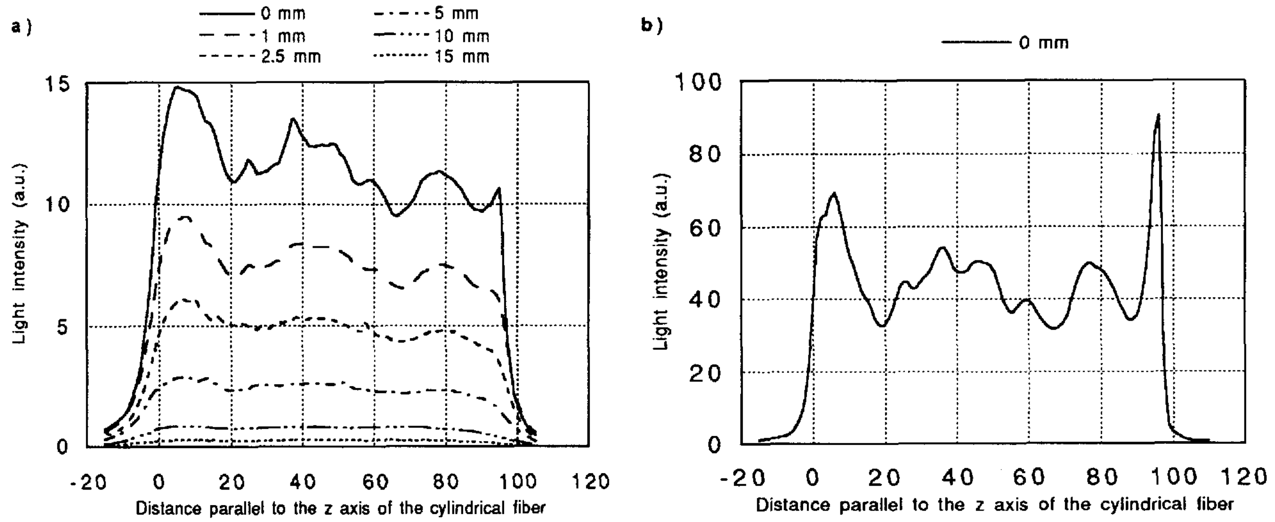

Fig. 6. (a) Longitudinal light intensity distribution measured parallel to a cylindrical fiber tip at different distances between detector and fiber surface. λ = 630 nm. The measurements are in a tissue phantom. (b) As in (a); however, the measurement is in air.

light distributor of this kind is shown in Figure 7 with an "active length" of only 25 mm. Here, the outside tube was in polypropylene (n = 1.49). In Figure 7a, the light intensity is measured along an axis parallel to the Z axis in the phantom with the omnidirectional probe at distances d = 0, 1, 2.5, 5, and 10 mm from the surface of the light distributor. For the two diffusers of Figure 7, light emission was purposely reinforced at both ends, so that the light intensity is homogeneous in the tissue at 5 mm depth. These distributors had an optical fiber diameter of 0.5 mm, the interior and exterior diameters of the outer tube were 0.6 mm and 0.9 mm, respectively, and they were equipped with and end mirror.

Figure 7b shows results obtained with a distributor exactly like that of Figure 7a with only the outer tube changed from polypropylene (a) to polyamide (b). Changing the outer tube from n = 1.49 (polypropylene) to n = 1.51 (nylon) should not change the light distributor significantly so that the observed changes are probably due to changes in the local roughness induced on the core surface.

Figure 8 shows the dependence of the light distribution, which is here measured in air, using a different detector, as a function of the wavelengths. Clearly, both wavelength give similar distributions as is expected from basic principles for this type of light diffuser.

The type of light distributor presented above will accept up to ~4 Watts of light in the wavelength range discussed if the core is at least 500 μm in diameter. Increasing the diameter of the core allows higher powers to be used.

Figure 9 shows a schematic diagram of a complete fiberoptic light distributor of this kind. The proximal end of the fiber with the protective jacket diameter of 1.5 mm is mounted in an optical connector (SMA, ST, Radiall PFO, etc.). The distal end of the jacket is glued to the outer tube of the fibertip, whereas the fiber continues to the end of the diffuser. This method of fabrication is simple and easy to effect. The distributor produced in this way is both robust and flexible with a possible radius of curvature of the order of 10 mm. Furthermore, it is not very sensitive to chemical attack, so that it can easily be sterilized after treatment.

CONCLUSION

A novel type of cylindrical optical fiber has been realized using radial coupling between fiber core and diffusing medium. The amount of coupling of light out of the core is governed locally by the induced surface roughness. The light coupled out of the core is then rendered isotropic by adding a transparent polymer layer containing scattering TiO_2 particles. In between this layer and the core, there is a clear polymer layer that acts as an optical spacer. The homogeneity of such cylindrical distributors can be made close to perfect by controlling the local surface roughness. One such a diffuser functions over a large domain of

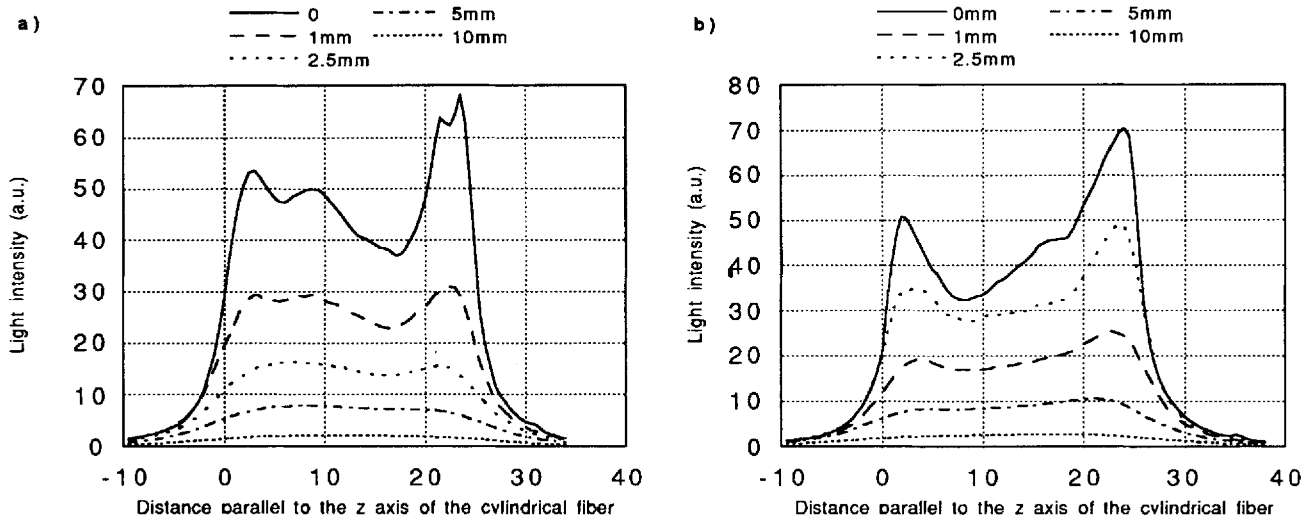

Fig. 7. Light intensity measured along an axis parallel to the distributor z axis at different distances in an optical phantom: (**a**) outer tube of the distributor is made in polypropylene, (**b**) outer tube of the distributor is made in polyamide.

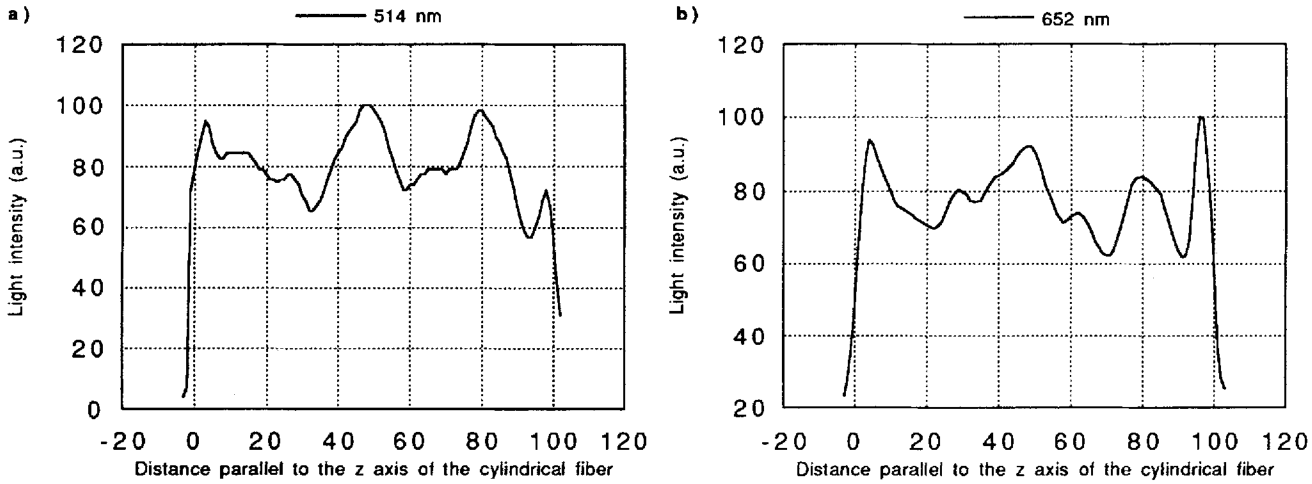

Fig. 8. These two curves demonstrate the wavelength independence of the present type of light distributor: (**a**) λ = 514nm, (**b**) λ = 652 nm. The measurements are in air at 1 mm from the surface of the fiber tip.

wavelengths. If desired, special inhomogeneous profiles also can be introduced. Only radially symmetric devices were considered here, but nonsymmetric devices, e.g., 180° instead of 360° distributors are also possible. The devices realized above are roughly 1 mm in diameter, but much smaller diameters are possible. Among the major advantages of such a system are: (1) no direct interface between the waveguide with its high intensity and the scattering medium, i.e., no risk of local heating at such an interface, (2) the possibility of making extremely long fiber tips with nearly any desired profile, and furthermore, the profile of light intensity does not depend on the refractive index of the surrounding tissue, and (3) the structure is fairly rigid so it can be used for interstitial applications, but when forced somewhat can be bent at quite tight angles (minimum bend radius <10 mm).

ACKNOWLEDGMENTS

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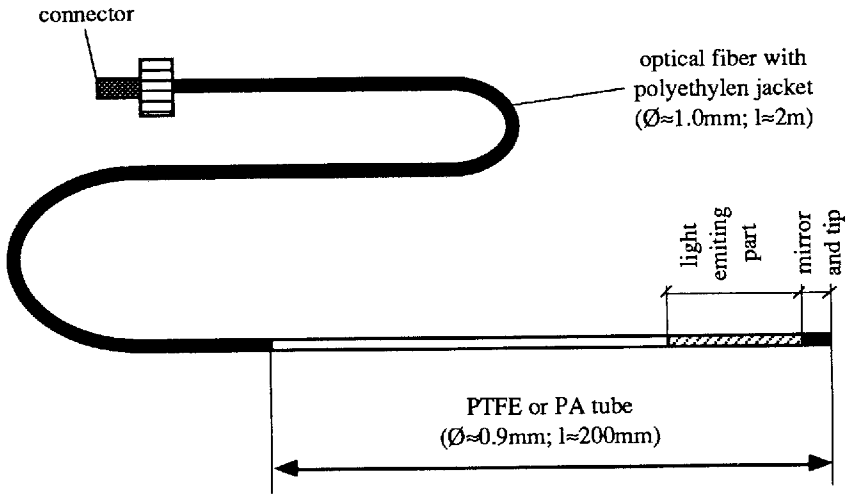

Fig. 9. Schematic diagram of this type of radial light distributor on the end of an optical fiber.

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APPENDIX

Materials

Fiber optic with a core of polymehylmethacrylate (PMMA) -refractive index: 1.492- and a cladding of fluorinated polymer -refractive index: 1.419- type PFU (Toray Industries, Japan), which can be obtained in diameters 0.5, 0.75, 1.0, and 1.5 mm or type PFS in diameter 0.25 mm.

Tubes in PTFE or polyamide (nylon 6), with the internal diameter ~100 μm larger than the outer diameter of the optical fiber, and length l_1.

PTFE or polyamide wire with the outside diameter equal to the inner diameter of the outer tube.

A cylindrical metallic mirror polished on one end-face with its diameter equal to the inner diameter of the outer tube.

Silicone elastomer consisting of a resin (part A) and a hardener (part B), Rhône-Poulenc Rhodorsil RTV 141.

Surface primer MB for the Rhodorsil elastomer.

TiO_2 particles of diameter ~200 nm, Al_2O_3 particles of diameter ~30 μm.

Fabrication Procedure

A. Polishing of the fiber tip down to a grain of 0.3 μm.
B. Removal of the cladding and roughening of the optical fiber over the desired "active" length of the fiber tip (l_2). This can be done for instance using special sandpaper for optical polishing with 2:1 (H_2O, ethanol) as a solvent. Note that the PMMA is not very resistant to most organic solvents. In practice, it is possible to control the roughening of the core by the following measurement. Inject the light of a HeNe laser in the fiber. The roughening of the surface goes hand in hand with increased light emission, which can be measured quantitatively after adding a little silicone with the appropriate refractive index. In those regions where the roughening is not sufficient, the silicone is removed by washing with soap and

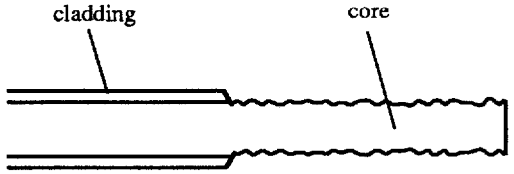
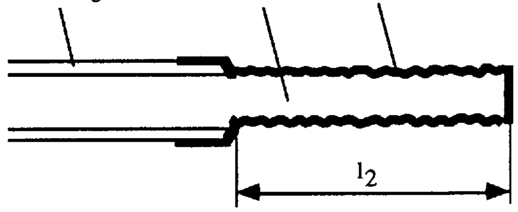


Fig. A1.

water followed by dilute ethanol, and the roughening is then pursued. It is also possible to repolish part of the core that has been roughened too much, using polishing sandpaper with a smaller grain size. It should be noted that for the production of light distributors with more perfect intensity distributions, and/or for the production of larger series, automatized and more optimal procedures have been envisaged.

C. When the correct light intensity profile has been obtained, both along the Z axis, and symmetrically for all 360° around the tip, the silicone is removed from the core and a primer (MB, Rhône-Poulenc) is painted onto the core to increase the adherence of the silicone elastomer. The solvent for the primer is methanol. The primer is then left to dry for ~1/2 hour.
D. A thin layer of liquid silicone elastomer (parts A and B) is then applied after having been degassed by pumping it down to ~20 mbar. The polymerization is done with the fiber in vertical position (distal end up) during 24 hours so that excess elastomer can flow away.
E. Introduction of degassed liquid silicone elastomer (parts A + B) over a length of 1/3 l_1 into the protective PTFE (or other) outer tube. This elastomer may or may not be loaded with TiO_2 particles. This is done by applying suction to the other end. After that, another length (1/3 l_2) is filled, again by suction, with silicone loaded with a fraction of TiO_2 particles and a much smaller fraction of Al_2O_3 particles of between 10 μm and 30 μm diameter. The fraction of TiO_2 in the silicone liquid is of the order of 1–5% by weight and depends on the distance between the core covered with pure elastomer and the outer tube. It is adjusted so that ~1–2 scattering events take place before the light reaches the outer tube. The concentration of the large diameter Al_2O_3 particles is at least a factor of 10 less. Its main purpose is to act as a spacer between the covered core and the outer tube, so that the former is centered in the latter.



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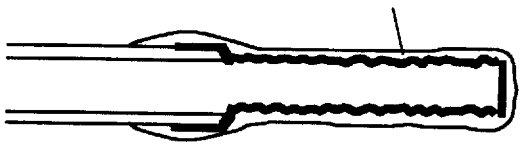


Fig. A3.

F. Introduction of the cylindrical metal mirror with the polished surface toward the fiber core. This mirror has been coated with a thin layer of primer for better adherence. It is pushed sufficiently far down the outer tube to leave room for a stopper.
G. The stopper then is placed against the mirror and held in place with a clamp. The fiber tip is now introduced carefully and slowly into the outer tube from the other end without introducing air bubbles. It is pushed against the mirror surface. The liquid silicone loaded with TiO_2 and Al_2O_3 particles should cover the full length of l_2, i.e., the full length of the roughened core. Polymerization at ambient temperature now takes 24 hours.
H. The stopper is now pulled out of the end of the outer tube. An appropriate metallic stopper with a sharp end for interstitial applications can now be inserted and glued in place as shown below. Clearly, in some cases the metal mirror may be replaced by a transparent stopper, and the sharp metal tip by a transparent plastic one of similar or different shape so as the allow for simultaneous forward illumination.

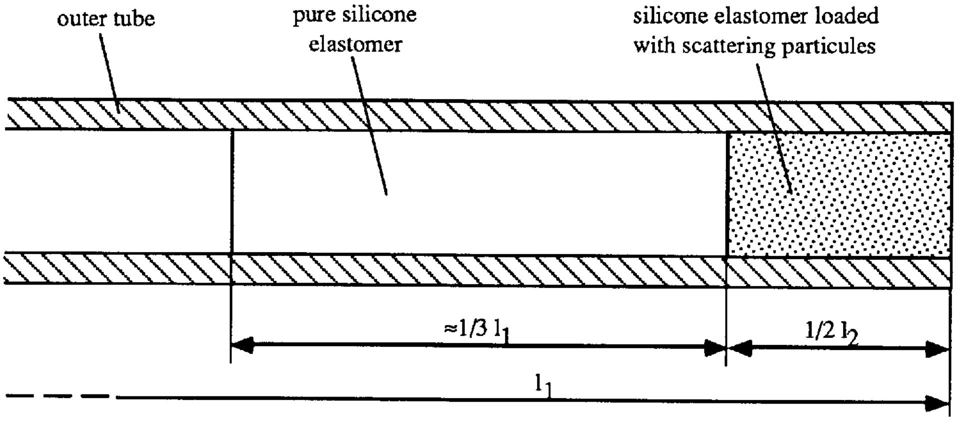
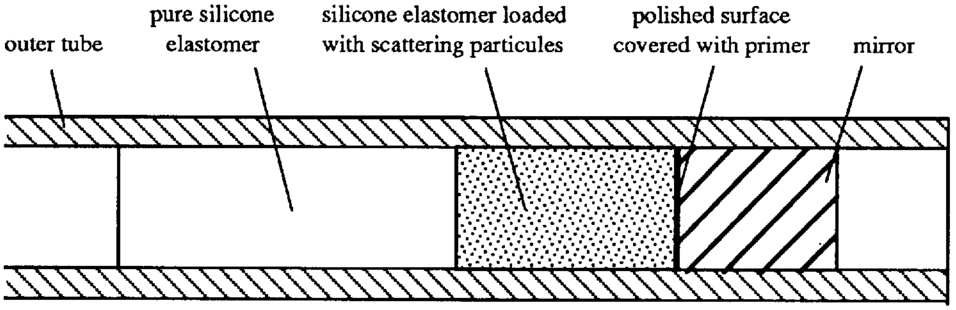


Fig. A4.



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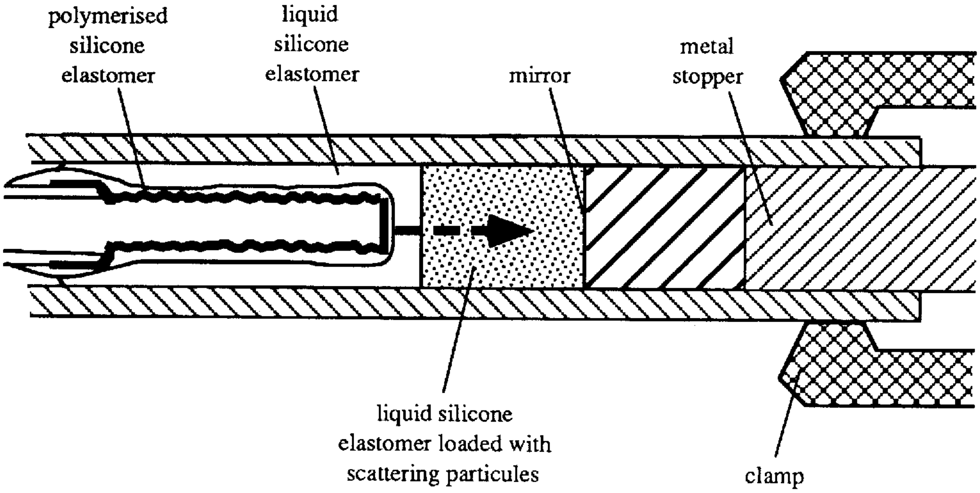

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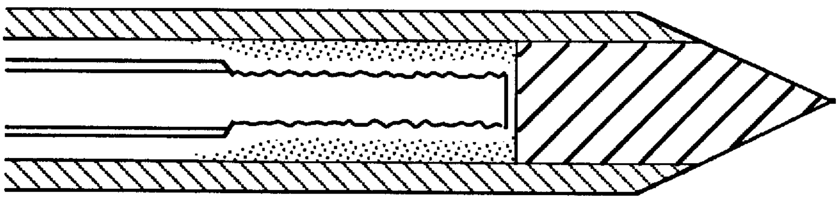

Fig. A7.